Technical Note N-1295

IN-SITU STRENGTH OF SEAFLOOR SOIL DETERMINED FROM TESTS ON PARTIALLY DISTURBED CORES

By

H. J. LEE

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NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California 93043

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ABSTRACT

The major obstacle to rational design of seafloor foundations and anchors has been a lack of good quality information on the bottom sediment engineering properties. Considerable engineering property data have been obtained through laboratory testing of core samples, but most of these data are of questionable validity because of the sample disturbance factor. To improve the usability and credibility of laboratory test data, an experimental investigation was undertaken to determine the extent of disturbance involved in seafloor soil sampling and handling. In-situ tests were performed and related to comparable laboratory tests. The soils tested were from the Santa Barbara Channel with a terrigenous (land-derived) origin. A technique based on earlier work was developed for predicting in-situ shear strength on the basis of laboratory test results. Various disturbance mechanisms including sampling, vibration, long-term nonrefrigerated storage, and water and air expansion were investigated and analyzed quantitatively. Strength reductions varying between 15 and 50 percent were observed to result from these disturbances. The in-situ strength prediction procedure appears to be capable of compensating for all forms of disturbance except for those developing as a result of gas expansion.

CONTENTS

INTRODUCTION

Obtaining reliable engineering properties of seafloor sediments is a complex and potentially very expensive proposition. The seafloor is remote, the sea is often hostile, and the sediments are unusually soft. Good quality sampling is difficult, and testing in-situ requires expensive equipment and considerable ship time. This situation can be improved either through the development of more economical in-situ test equipment or through better utilization of soil samples. The latter approach was taken in this report.

The major problem in engineering property testing of seafloor soil samples in the laboratory has been disturbance. During sampling, transportation, and preparation of specimens, changes occur in the material, causing it to behave differently in the laboratory than it would have behaved in the field. This problem is more severe with seafloor soils than with land soils because the material is generally softer, the usual types of samplers are more destrictive, and the amount of total stress change during sampling is significantly greater.

A testing program was formulated to investigate the general problem of sample disturbance with the following specific objectives:

1. Evaluate the quality of samples taken with the NCEL DOTIPOS bottom-sitting fixed-piston coring equipment (Demars and Taylor, 1971).
2. Determine how the DOTIPOS core quality compares with that of more conventional gravity cores.
3. Determine how various forms of disturbance affect the quality of the DOTIPOS cores.
4. Develop procedures for estimating in-situ strength given results of tests on partially disturbed cores.

DISTURBANCE MECHANISMS

A number of possible disturbance mechanisms were identified through a review of the literature. These disturbance mechanisms, with the exception of core shortening and direct temperature effects, were investigated either experimentally or analytically. The results of these investigations are presented in later sections.

In-Situ Shear Stress Removal

The in-situ stresses on a soil element are usually anisotropic, in that the horizontal and vertical stresses are not equal. During sampling the element is removed from the ground and then later

transported, stored, trimmed, and tested. A number of researchers (Noorany and Seed, 1965; Ladd and Lambe, 1963; Skempton and Sowa, 1963; and Beard, 1972) have investigated the hypothetical process in which no sample disturbance occurs other than that involved in the release of the in-situ shear stresses. The term "perfect sampling" has been used by these investigators in the past to describe this process. This term is actually incorrect since some disturbance does occur during the process. In this report the term, "in-situ shear stress removal," will be used in place of "perfact sampling." The researchers above have determined that strength reductions on the order of five percent may result from in-situ shear stress removal when sampling clayey soils. Somewhat greater reductions may result with silty soils.

Mechanical Disturbance

One of the most common forms of disturbance is that resulting from routine handling, possible mishandling, and cutting of samples. These activities result in a certain amount of soil particle reorientation and interparticle bond breaking. The shear strength is usually decreased, and the compressibility increased.

Probably the greatest amount of mechanical disturbance occurs when the sample is taken from the ground. Suggestions as to how this disturbance may be reduced through good sampler design are given by Hvorslev (1949), Jakobson (1954), and Kallstenius (1958). Most of the common seafloor sediment samplers fall considerably short of satisfying the criteria of these researchers.

Pore Water Expansion

Water is a slightly compressible medium to the extent that for every 10,000 feet of water depth increase the water is compressed by about 1.5 percent. When a sample is taken, therefore, the pore water expands by the same amount. Several writers (Monney, 1967; Richards and Parker, 1967; and Crisp, 1968) have expressed concern that water expansion may alter soil engineering properties, but an indication of the possible extent has not been provided.

Gas Expansion

Some sediments contain large quantities of dissolved gas, usually methane. When these sediments are sampled and brought to the surface, most of the gas comes out of solution. This is a much more serious problem than water expansion because gas is considerably more compressible and forms bubbles when it comes out of solution. Therefore, the disturbance is concentrated at localized points where the integrity of the interparticle bonding can be totally destroyed.

Temperature Effects

Typical seafloor temperatures are in the vicinity of $4^{\circ}C$. When a sample is obtained and special precautions are not taken, the sample temperature may rise by $30^{\circ}C$ or more. This will result in water expansion on the order of 0.5 percent. Since temperature changes occur gradually, there is little chance of the grain structure being disturbed. However, some water may be expelled. It has been shown (Mitchell, 1969) that if the temperature is lowered again, the sample may appear stronger or less compressible than it would have otherwise. Mitchell recommends that testing should be performed at the highest temperature the soil has ever experienced.

Temperature also has been shown to have an influence on time-rate-dependent soil responses (Singh and Mitchell, 1968), such as secondary compression and shear creep. When these soil responses are of critical importance, samples should be maintained at seafloor temperatures continuously through the testing process.

Organic Material Decomposition

Seafloor soils often contain large quantities of organic material. At seafloor temperatures, growth or decomposition of the material is retarded. If the temperature of the sample is increased, the rates of growth or decomposition may be greatly accelerated. Gases may be generated, and the properties of the soil may be altered. Richards and Parker (1967) discuss core samples that have exploded on deck because of gases generated during organic matter decomposition. Although core sample explosions are rare, it is reasonable to assume that severe disturbance may result from this phenomenon in many situations.

Water Content Changes

Samples can change their water contents through a variety of mechanisms; included are pore fluid expansion, drying as a result of improper sealing, and swelling as a result of storing the sample under water. Since disturbance leads to increased sample compressibility, partial consolidation within well-sealed core liners can also occur. Vertical sample storage would probably lead to a greater amount of consolidation than horizontal storage.

Long-Term Storage

A number of creep mechanisms can be operative over the long-term period which would result in changes in the engineering response. Vibrations (for example, from a refrigerator motor) could accelerate creep rate.

Core Shortening

With almost all of the standard oceanographic coring devices, it is often difficult to determine the depth below the seafloor from which a particular sample is obtained. A plug may form in a gravity corer and cause weak strata to be pushed away and not sampled. A piston corer in which the piston is not fixed relative to the seafloor may suck in quantities of soft material. In both cases the depth of a sample within the core will not correspond to its original depth below the seafloor. Richards and Parker (1967) present a discussion of the problem and offer some tentative techniques for evaluating its effects.

TEST PROGRAM

A test plan was developed in which the undrained shear strength of soil from different seafloor sites would be measured under a variety of situations ranging from in-situ to a moderately disturbed sample. The samples were subjected to specific forms of disturbance so that the influence of each, in terms of changes in strength, could be determined. More importantly, the data could be used to develop procedures for estimating the in-situ strength when given the strength of a partially disturbed sample.

To develop a procedure for correcting strengths for disturbance, it was necessary to have a measure of the amount of disturbance to which the sample had been subjected. From a review of the literature (Ladd and Lambe, 1963; Noorany and Seed, 1965), it was determined that the most commonly used disturbance parameter is the residual pressure retained by the pore water within each sample. These pressures are negative relative to atmospheric, and, in general, the more negative the pressure, the smaller the amount of disturbance. These pressures develop because of the natural tendency of soil to expand during sampling as a result of the release of in-situ stress. In relatively fine-grained soils this expansion is retarded by the development of menisci in the pores near the sample surface, with a general state of tension being set up throughout the samples pores. As the sample is disturbed, however, these tensile stresses are gradually broken down.

The general procedure followed in the experimental program was to measure in-situ strength, the strength of samples with varying degrees of disturbance, and the residual negative pore water pressure. The data were then analyzed to determine how the in-situ strengths could be estimated given the sample strengths and the residual pore pressures. This involved an empirical correlation of the measured parameters.

Coring Program

At least five 10-foot, fixed-piston cores were taken at each of three sites in the Santa Barbara Channel area off Southern California. The coring system used operates in conjunction with the DOTIPOS platform (Padilla, 1971) and has been described previously (Demars and

Taylor, 1971). The corer was designed according to the criteria mentioned earlier so as to yield high quality samples. Each core was cut into 2-foot increments on shipboard, sealed with vinyl electrician's tape and a mixture of paraffin and silicon wax, and stored at near sea-floor temperatures (39°F).

In addition, at least one gravity core was taken at each site using a corer designed by A. Richards of Lehigh University (designed using criteria of Richards and Parker, 1967). This corer contains many improved design features including a large diameter, plastic core barrel.

The three sites are shown on the map of Figure 1 and have the coordinates given in Table I. In this report the sites will be referred to by their water depths: 100-foot site, 600-foot site, and 1200-foot site. Additional laboratory and in-situ test data on the soils at the 100-foot and 600-foot sites are given by Demars and Taylor (1971), Taylor and Demars (1971), Kretschmer and Lee (1970), and Herrmann and others (1972). The characteristics of this 1200-foot site have not been reported previously; the index properties for it are given in Table II.

In-Situ Tests

At least one field vane shear and one cone penetration test were performed at each site. NCEL's vane shear and cone penetrometer device (Demars and Taylor, 1971) was used in conjunction with the DOTIPOS platform. The vane and cone results are given in Figures 2 and 3.

Laboratory Tests

Miniature vane, residual pore pressure, and water content tests were performed on selected samples obtained from the various cores. The vane tests were performed in the usual manner (Demars and Taylor, 1971). Both field and laboratory vane tests were performed at the same rotation rate - one revolution per hour. Therefore, since the field vanes are larger in diameter than the laboratory vanes by about a factor of four, there is a difference between the tangential velocities of the vane tips. This could lead to systematic differences in strength separate from disturbance effects. However, on the basis of previous research on vane rotation rate effects (Migliore and Lee, 1971; Halwacks and Monney, 1972), it appears as if these systematic differences are minimal (less than ten percent change in strength).

The residual negative pore pressure was measured with a device consisting of a pressure transducer connected to a ceramic disk with a nominal air penetration pressure of one bar. The ceramic disk was placed in contact with a flat soil surface, and the residual pressure was transferred across the disk to the transducer. Some time (as long as 30 minutes) was required for stabilization of pressures. Techniques similar to these have been used previously by Gibbs and Coffey (1969).

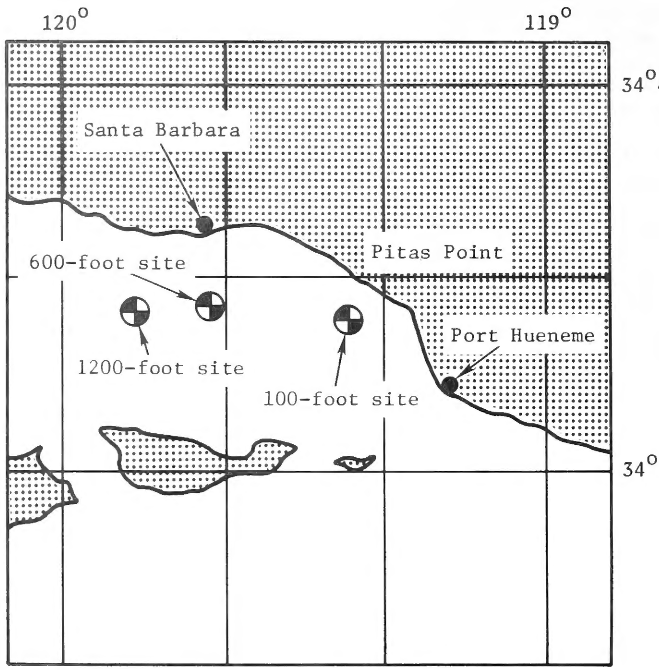

Figure 1. Test site locations.

Table I. Test Sites and General Conditions

Site Designation*	Location	Longitude	Latitude	General Soil Characteristics**
100-foot site	Near Pitas Point	119°24'15"W	34°16'45"N	A relatively uniform clayey silt (ML by the Unified Soil Classification System) to around 8 feet where a significantly stronger strata occurs. Median grain size of about 0.01 mm, plastic limit of 28 percent, and liquid limit of about 44 percent. Relatively sensitive.
600-foot site	Location of SEACON I Experiment	119°42'47"W	34°17'12"N	A somewhat nonuniform deposit which varies from a sandy, clayey silt (ML) in the upper 3 feet to a clayey silt (ML-MH) below. Median grain size varies between 0.03 and 0.01 mm. Material appears to be overconsolidated and is unusually strong. Plastic limit of lower material is about 37 percent; liquid limit, 65 percent.
1200-foot site	Near Isla Vista	119°50'58"W	34°16'30"N	A uniform plastic, clayey silt (MH). Median grain size of about 0.008 mm, plastic limit of 41 percent, and liquid limit of 83 percent. Appears most nearly typical of deeper sea sediments.

* Numbers refer to water depth
** All soils tested are of terrigenous (land-drived)origin

Table II. Index Properties of 1200-Foot Site

Depth (ft)	Core	Specific Gravity of Grains	Median Grain Size (mm)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index	Classification*
0.13	EP-13	2.58	0.009	87.3	38.9	48.4	MH
1.13	EP-16	2.57	0.008	86.3	41.4	44.9	MH
2.13	EP-12	2.57	0.009	89.2	42.5	46.7	MH
3.13	EP-13	2.58	0.009	86.1	40.2	45.9	MH
4.13	EP-16	2.58	0.008	80.4	40.7	39.7	MH
5.13	EP-13	2.57	0.009	78.3	41.6	36.7	MH
6.13	EP-12	2.56	0.008	90.6	40.8	49.8	MH
7.13	EP-12	2.57	0.008	73.8	43.4	30.4	MH

* Unified Soil Classification

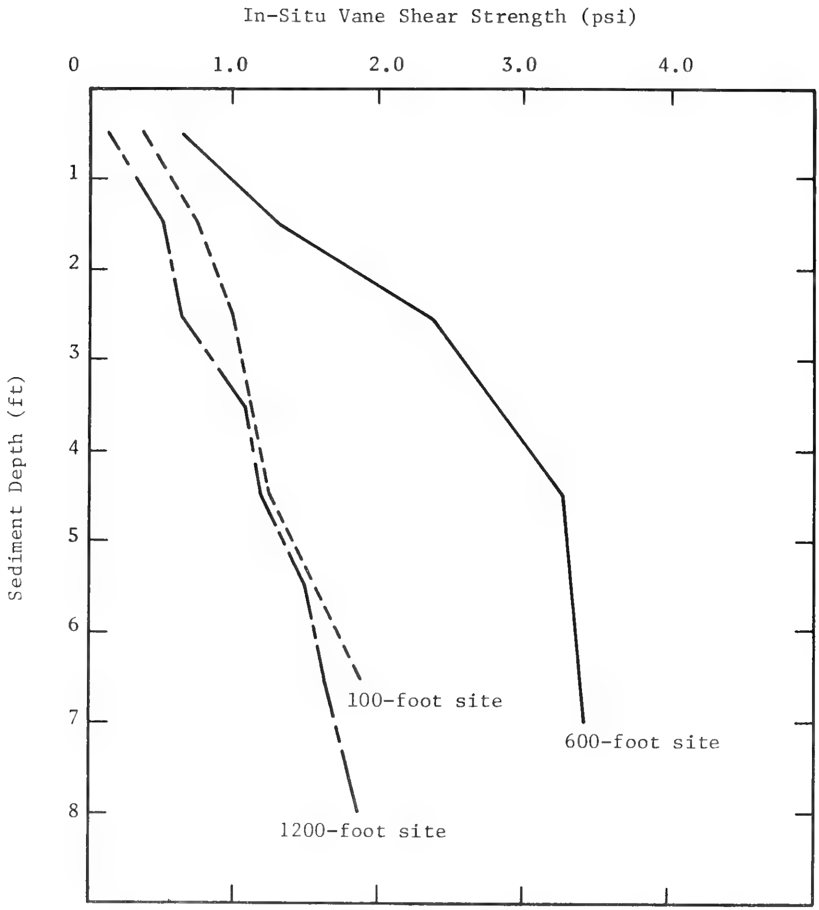

Figure 2. In-situ vane shear test results (average for each site).

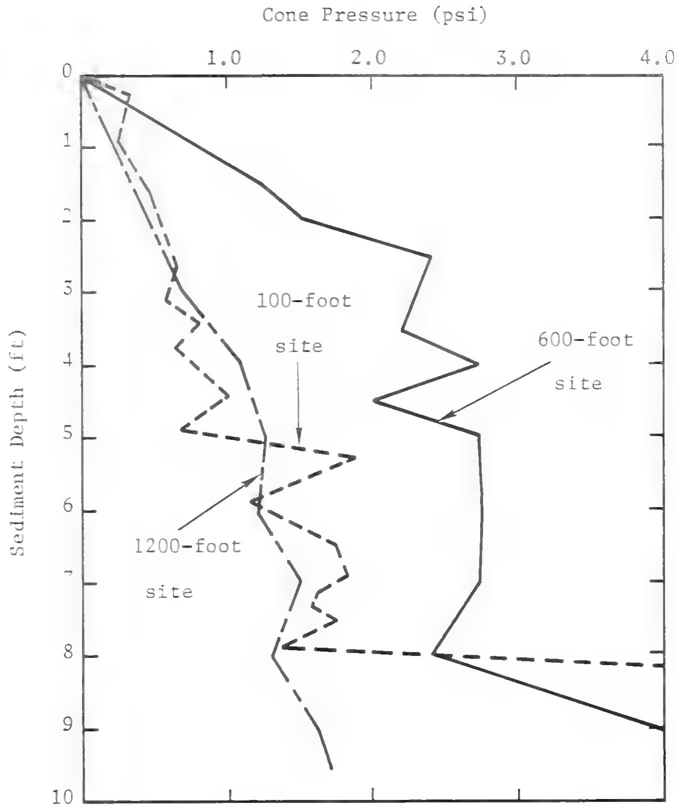

Figure 3. In-situ static cone penetration tests (average for each site).

The samples were treated in different ways so that various effects of disturbance could be analyzed. The types of treatment were as follows:

Standard. Samples were stored under refrigerated, 100 percent humidity conditions and tested as soon as possible. Vibrations and other forms of mechanical disturbance were minimized. It was originally intended to store these samples vertically, as has been the standard practice in oceanographic work. However, after a few weeks, it became apparent that vertical storage was leading to partial consolidation. All samples were then laid horizontally for the remainder of the program.

Nonrefrigerated Storage. Samples were maintained at approximately 75°F during the period before testing (1 to 6 months), but otherwise treated as "standard."

High-Frequency Vibration. Samples were vibrated for 30 minutes at 40 KHz in an ultrasonic cleaner before testing, but otherwise treated as "standard."

Low-Frequency Vibration. Samples were vibrated for 60 minutes at 27 Hz on a sieve shaker before testing, but otherwise treated as "standard."

Long-Term Storage. Samples were stored for slightly over one year before testing, but were otherwise treated as "standard."

Very Long Term Storage. A set of samples is being retained for testing after two or three years to determine the influence of very long storage. Results of this extended storage will be presented in a later report.

An experimental design was developed so that the influence of each of the deviations from standard could be determined for each of the test sites and for each sediment depth range. The test plan and laboratory test results (initial and remolded vane shear, residual negative pore water pressure, and water content) are listed in Tables III, IV, and V. The tests, with the exception of those subjected to long-term storage, were performed in a random order.

About 50 triaxial tests (consolidated and unconsolidated-undrained with pore pressure measurements) were performed on samples taken from these cores. The complete results and a description of the testing techniques will be presented in a later report on the shear strength of cohesive seafloor soils.

In addition, a supplementary study of the characteristics of in-situ shear stress removal ("perfect sampling") was undertaken using samples from the 100-foot site. It was found that in-situ shear stress removal alone could account for as much as a 15 percent reduction in strength when dealing with a silty material like that at the 100-foot

Table III. Laboratory Test Results at 100-Foot Site

Core No.	Sediment Depth (in)	Treatment*	Initial Vane Strength, S_L (psi)	Remolded Vane Strength (psi)	Residual Pore Water Pressure Before Vane Test, u_r (psi gage)	Water Content (%)
EP-8	0-3	standard	0.25	0.05	-0.04	73
	12-15	very long term				
	24-27	low frequency	0.75	0.11	-0.07	52
	36-39	standard	0.82	0.09	-0.19	51
	48-51	nonrefrigerated	0.65	0.05	-0.14	50
	60-63	high frequency	0.50	0.08	-0.06	44
	72-75	standard	1.46	0.30	-0.23	46
	84-87	long term	2.18	0.51	-0.22	38
	96-99	standard	3.69	0.62	-0.43	36
EP-9	8-9	long term	0.46	0.13	-0.09	57
	12-15	standard	0.57	0.11	-0.09	53
	24-27	high frequency	0.61	0.13	-0.07	52
	36-39	standard	0.43	0.10	-0.19	55
	48-51	standard	0.43	----	-0.10	47
	60-63	low frequency	0.58	0.07	-0.01	43
	72-75	very long term				
	84-87	standard	0.85	0.16	-0.31	45
	96-99	nonrefrigerated	1.27	0.07	-0.14	37
EP-10	0-3	standard	0.24	0.03	-0.07	48
	12-15	nonrefrigerated	0.45	0.12	-0.07	53
	24-27	standard	0.76	0.14	-0.18	46
	36-39	long term	0.61	0.17	-0.15	57
	48-51	very long term				
	60-63	standard	0.78	0.22	-0.27	42
	72-75	high frequency	0.72	0.12	-0.17	44
	84-87	low frequency	0.93	0.13	-0.21	43
	96-99	standard	3.48	0.73	-0.76	38
PPG-1 (Lehigh Corer)	9-12	standard	0.36	0.15	-0.08	56
	21-24	standard	0.45	0.16	-0.09	55
	33-36	standard	0.71	0.19	-0.14	50
	45-48	standard	0.65	0.18	-0.17	44

* Tests under "very long term" storage will be performed at a later date.

Table IV. Laboratory Test Results at 600-Foot Site

Core No.	Sediment Depth (in)	Treatment*	Initial Vane Strength, S_L (psi)	Remolded Vane Strength (psi)	Residual Pore Water Pressure Before Vane Test, u_r (psi gage)	Water Content (%)
EP-1	0-3	standard	0.56	0.08	-0.13	74
	12-15	very long term				
	24-27	low frequency	1.88	0.54	-0.44	39
	36-39	standard	1.99	0.61	-0.67	46
	48-51	nonrefrigerated	----	----	-0.69	66
	60-63	high frequency	2.07	0.29	-0.78	56
	72-75	standard	2.29	0.70	-0.72	50
	84-87	long term	3.46	1.36	-0.92	52
	96-99	standard	4.55	1.86	-0.89	51
	108-111	standard	5.08	1.25	-1.67	46
EP-3	0-3	long term	0.32	0.13	-0.13	70
	12-15	standard	0.89	----	-0.29	51
	24-27	high frequency	1.90	0.39	-0.11	39
	36-39	standard	3.27	0.56	-0.32	42
	48-51	standard	2.11	0.45	-0.80	59
	60-63	low frequency	2.95	0.86	-0.92	46
	72-75	very long term				
	84-87	standard	1.32	0.32	-1.33	53
	96-99	nonrefrigerated	3.40	0.62	-0.53	44
EP-4	0-3	standard	0.32	0.06	-0.09	77
	12-15	nonrefrigerated	0.65	0.13	-0.06	51
	24-27	standard	1.60	0.35	-0.27	45
	36-39	long term	0.90	0.20	-0.14	58
	48-51	very long term				
	60-63	standard	2.63	0.63	-1.37	57
	72-75	high frequency	2.45	0.66	-0.42	47
	84-87	low frequency	3.21	0.95	-0.76	59
	96-99	standard	3.76	0.50	-0.70	59
EPG-1 (Lehigh Corer)	9-12	standard	0.71	0.20	-0.16	49
	24-27	standard	2.13	0.93	-0.48	46

* Tests under "very long term" storage will be performed at a later date.

Table V. Laboratory Test Results for 1200-Foot Site

Core No.	Sediment Depth (in)	Treatment*	Initial Vane Strength, S_L (psi)	Remolded Vane Strength (psi)	Residual Pore Water Pressure Before Vane Test, u_r (psi gage)	Water Content (%)
EP-12	0-3	standard	0.25	0.06	-0.12	126
	12-15	very long term				
	24-27	low frequency	0.72	0.27	-0.11	93
	36-39	standard	1.40	0.20	-0.17	85
	48-51	nonrefrigerated	0.96	0.26	-0.25	88
	60-63	high frequency	0.94	0.18	-0.38	82
	72-75	standard	2.28	0.93	-0.91	87
	84-87	long term	1.67	0.58	-0.57	84
	96-99	standard	1.65	0.56	-0.87	80
EP-13	0-3	standard	0.23	0.04	-0.13	129
	12-15	nonrefrigerated	0.46	0.15	-0.10	88
	24-27	standard	1.17	0.37	-0.55	84
	36-39	long term	0.45	0.11	-0.19	93
	48-51	very long term				
	60-63	standard	1.11	0.40	-0.67	87
	72-75	high frequency	1.22	0.25	-0.45	85
	84-87	low frequency	1.68	0.63	-0.60	79
	96-99	standard	1.96	0.61	-0.65	77
EP-16	0-3	long term	0.94	0.40	-0.27	85
	12-15	standard	0.52	0.12	-0.15	102
	24-27	high frequency	0.41	0.35	-0.22	82
	36-39	standard	1.12	0.35	-0.71	88
	48-51	standard	1.22	0.52	-0.61	86
	60-63	low frequency	1.14	0.15	-0.33	84
	72-75	very long term				
	84-87	standard	0.87	0.41	-----	83
	96-99	nonrefrigerated	1.43	0.18	-0.57	83
EPG-2 (Lehigh Corer)	12-15	standard	0.56	0.17	-0.22	100
	21-24	standard	0.54	0.13	-0.21	98
	33-36	standard	1.11	0.45	-0.57	85
	46-49	standard	1.21	0.45	-0.22	79

* Tests under "very long term" storage will be performed at a later date.

site. The complete results of this study were reported in a UCLA masters thesis (Beard, 1972).

ANALYSIS

The major portion of the data analysis phase of this investigation involved developing a procedure for predicting in-situ strength given tests on partially disturbed samples. As discussed previously, the approach selected for this development was the derivation of correlations between measured parameters including sample vane shear strength, sample residual pore pressure, and field vane strength. It appeared as if the best means of developing this correlation was through a plot of the ratio of in-situ to sample strength versus the ratio of the measured residual pore pressure to a reference residual pore pressure indicative of the in-situ stress conditions. The residual pore pressure which would result from the removal of in-situ shear stresses and no other disturbance was selected as a suitable reference residual pore pressure. This reference pressure has been termed the "perfect sampling" residual pore pressure by previous investigators. The strength ratio is the desired quantity in any sample strength correction procedure. However, it is also a measure of the amount of disturbance the sample has undergone. Likewise, since the pore pressure ratio represents how the sample quality changes as the sample progresses from an "ideal" (reference) condition to an actual (final) condition, it is also a measure of amount of disturbance. Therefore, since both ratios are measures of the same quantity, they should correlate directly with each other. Of greater importance, however, procedures have been developed by Ladd and Lambe (1963) for estimating without in-situ test data, the residual pore pressure which would result from in-situ shear stress removal. Therefore, a good empirical correlation between the two ratios can be used practically to estimate in-situ shear strength. The pore pressure ratio can be calculated on the basis of laboratory tests. It can then be correlated with the strength ratio which can be used directly to calculate the in-situ strength when given the laboratory strength.

To calculate the reference residual pore pressure, Ladd and Lambe (1963) suggest the following equation:

$$-u_{ps} = \bar{\sigma}_{vo}\left[K_o + A_u(1 - K_o)\right] \quad (1)$$

where u_{ps} = reference residual pore pressure

$\bar{\sigma}_{vo}$ = in-situ vertical effective stress

K_o = coefficient of lateral earth pressure at rest (ratio of lateral to vertical in-situ effective stress)

A_u = reference pore pressure parameter

The in-situ vertical effective stress may be calculated easily by integrating the buoyant unit weight of soil overlying the sample in-situ with respect to depth. The parameter, A_u, can be related approximately to sediment type (Table VI, taken from Ladd and Lambe, 1963).

The parameter K_o is critical and may be difficult to estimate. If the soil is clearly normally consolidated, K_o may be assumed equal to about 0.5. Many surficial seafloor soils, however, display either true- or pseudo-overconsolidation effects, and K_o may differ significantly from 0.5. For these overconsolidated soils, Brooker and Ireland (1965) provide an empirical technique for estimating K_o through a plot relating plasticity index, K_o, and the overconsolidation ratio (maximum past pressure divided by present in-situ vertical effective stress). This plot, shown in Figure 4, appears to be a reasonable means of estimating K_o, although it does require the performance of a consolidation test to obtain the maximum past pressure (Casagrande, 1936).

Also, in using the curves of Brooker and Ireland (1965), it must be assumed that all soils which appear overconsolidated react in the same way in terms of lateral stress development. This assumption will need to be reexamined in future research since some overconsolidation effects may occur as a result of factors other than the removal of pre-existing overburden. The manner in which K_o varies during these other processes is currently not known.

In the present study a large number of consolidation test results were available (Herrmann, Rocker, and Babineau, 1972) for the 100-foot and 600-foot sites. Maximum past pressures were determined from these data and overconsolidation ratios were calculated. The 1200-foot site appeared to be normally consolidated (overconsolidation ratio of 1.0). The curves of Brooker and Ireland (1965) were entereed, and values of K_o were obtained. These were inserted into Equation 1 to obtain the reference residual pore pressure, u_{ps}. Table VII summarizes the parameters used in calculating the u_{ps} distribution at each site, and Table VIII lists the values of u_{ps} calculated.

Ratios of measured field to laboratory vane shear strength and measured to reference residual pore pressure were calculated. These ratios are plotted in Figure 5. There is considerable data scatter, possibly because each data point incorporates four inexact measurements or estimates. There does, however, appear to be a definite correlation between the two ratios.

To indicate the influence of the various forms of sample treatment and the soil type variations among the sites, the strength and pore pressure data for each treatment-size combination were averaged. A plot of these average points is presented in Figure 6. Here the correlation is significantly improved since a good deal of the random error is averaged out. Also plotted in this figure is a curve adapted from Ladd and Lambe (1963) for the well-known Weald clay, an estuarine deposit. Although this curve was developed strictly from laboratory testing using different parameters, Ladd and Lambe suggest that it should be used in an essentially identical way. It appears to fit the

Table VI. Reference Residual Pore Pressure Parameter, A_u (Ladd and Lambe, 1963)

Soil Type	A_u
Normally consolidated	
Clayey silt	-0.1 to 0.0
Lean clay	0.1 to 0.2
Plastic clay	0.2 to 0.3
Heavily overconsolidated	
Plastic clay	0.3

Table VII. Parameters Used to Obtain Reference Residual Pore Pressure, u_{ps}, at Each Site

Site	K_o	A_u
600-Foot		
0-3 ft	1.4	0.15
3-4 ft	0.9	0.15
5-6 ft	0.7	0.15
7-8 ft	0.8	0.15
1200-Foot	0.6	0.2
100-Foot	0.6	0.0

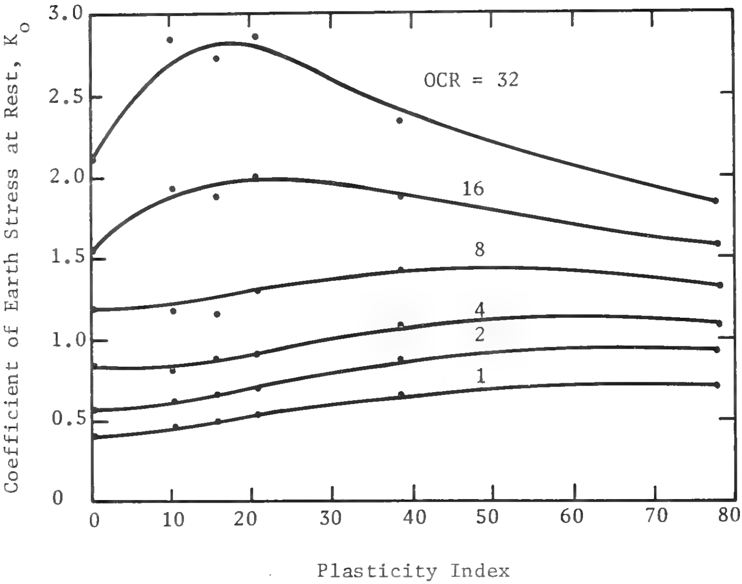

Figure 4. K_o as function of overconsolidation ratio and plasticity index. Overconsolidation ratio - OCR (From Brooker and Ireland (1965)).

Table VIII. Estimated Reference Residual Pore Pressure, u_{ps}, for Each Site

Site Depth (ft)	600-Foot	100-Foot	1200-Foot
0.13	-0.04	-0.02	-0.01
1.13	-0.42	-0.19	-0.12
2.13	-0.63	-0.36	-0.25
3.13	-1.27	-0.55	-0.40
4.13	-1.21	-0.73	-0.54
5.13	-1.14	-0.93	-0.60
6.13	-1.51	-1.13	-0.83
7.13	-1.75	-1.33	-0.97
8.13	-2.00	-1.55	-1.12

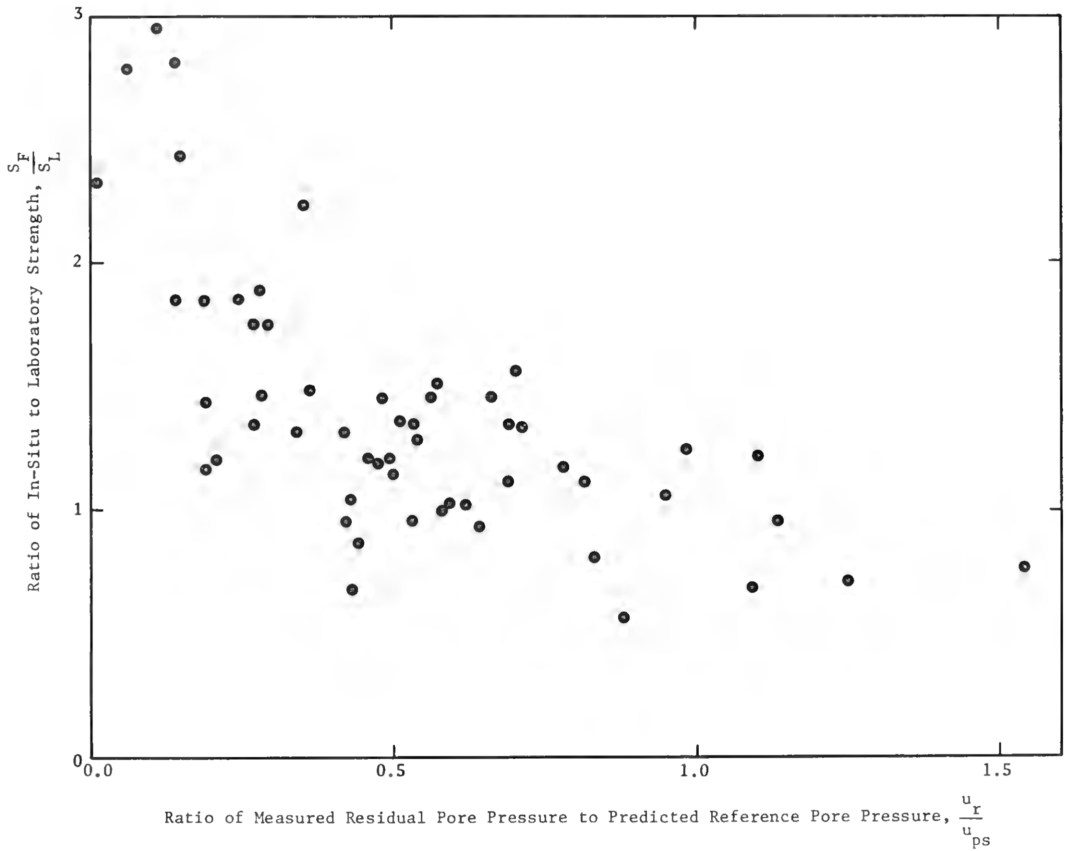

Figure 5. Normalized strength vs normalized residual pore pressure - all data.

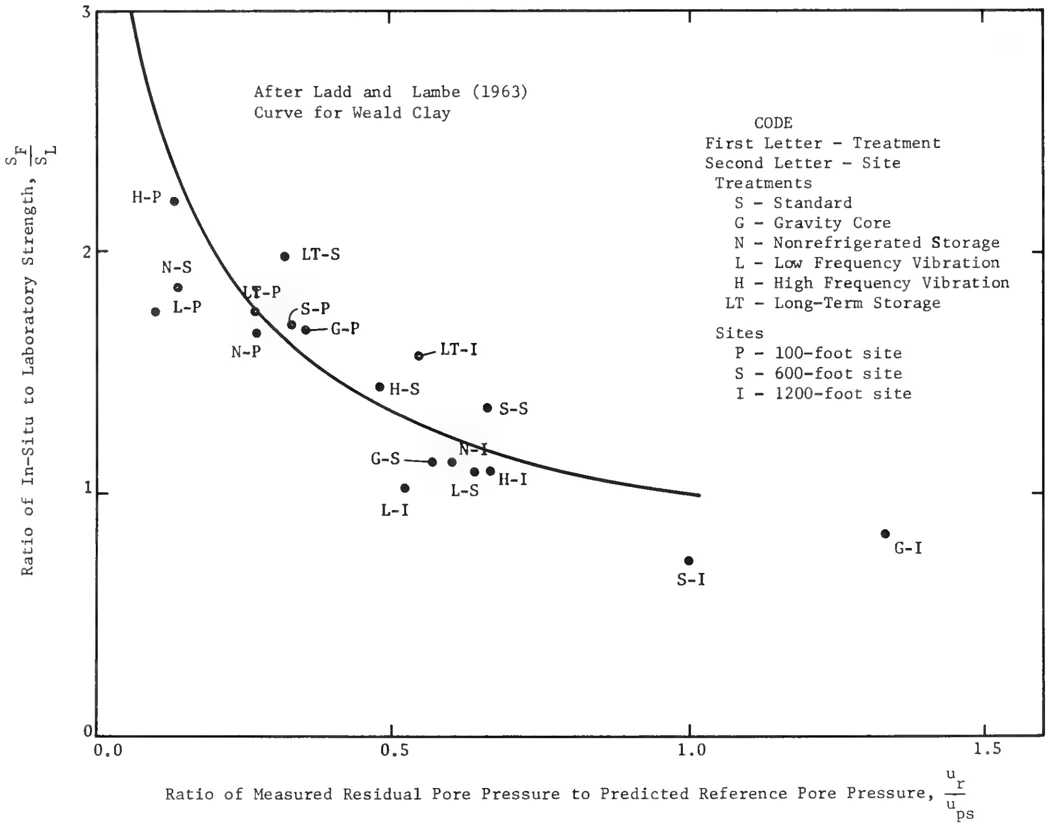

Figure 6. Normalized strength vs normalized residual pore pressure (average data for each treatment - site combination).

data of this study well and is, therefore, suggested for use in analyzing seafloor sediments of a similar nature. It should be noted, however, that Ladd and Lambe present curves for soils other than Weald clay, and, although most (5 out of 8) of the curves are similar, several differ significantly. Therefore, extrapolating these data to different materials (possible deep sea oozes and clays) may lead to error. Research on these soils is needed and is currently in progress at NCEL.

The data of Figure 6 are presented in numerical form in Table IX so that a comparison of the different treatments and soil types can be made. As can be seen, there are significant differences among the data, and the following observations can be made:

1. There is a strong variation in sample quality among the three sites. The silty, slightly plastic soil of the 100-foot site yielded laboratory strengths 40 to 50 percent lower than the in-situ values with correspondingly low residual pore pressure ratios. The more plastic, although equally coarse grained, samples from the 600-foot site were of better quality (20 to 30 percent strength reduction), while the plastic, clayey samples from the 1200-foot site were the highest in quality (almost no strength reduction). Some of this strength reduction is a result of in-situ shear stress removal, which is completely unavoidable. The extent of this disturbance is about 15 percent for the 100-foot site soils (Beard, 1972) and probably somewhat less for the other more plastic soils. One problem with the 1200-foot site is apparent: some of the strengths are higher than the in-situ values and the residual pore pressures are more negative than the reference pore pressures. This appears almost certainly to be a result of either partial drying or partial consolidation. Since the samples were well sealed, the possibility of consolidation during the period of vertical storage appears more probable.

2. The NCEL fixed piston and Lehigh gravity samples appear to be almost identical in quality although the NCEL equipment has the advantage of yielding longer cores. When subjected to standard practices, the samples from both corers were of sufficient quality to produce laboratory vane strengths within 30 percent of the field vane values for the more plastic 600- and 1200-foot sites. These values may be adequate for design without a disturbance correction. Both types of samples of the less plastic 100-foot site soils were more disturbed, with the amounts of disturbance almost identical for the two types of corers. For soils such as those at the 100-foot site, disturbance corrections would usually be required.

3. Low frequency vibration did not produce a significant change in the strength, although the residual pore pressure was less negative than for standard treatment.

4. High-frequency vibration caused large changes in residual pore pressure (except for the possibly partially consolidated 1200-foot site soils) with corresponding large changes in strength.

5. Long-term and nonrefrigerated storage had pronounced effects with average strength values on the order of 40 percent less than the field values.

Table IX. Average Normalized Strength and Normalized Residual Pore Pressure for Each Treatment-Site Combination

	Treatment*						
Site	Standard	Gravity Core	Nonre-frigerated Storage	Low Frequency Vibration	High Frequency Vibration	Long-Term Storage	Average
100-Foot	1.69 0.33	1.68 0.35	1.67 0.27	1.75 0.10	2.21 0.13	1.75 0.27	1.81 0.25
600-Foot	1.36 0.66	1.14 0.57	1.85 0.14	1.09 0.64	1.45 0.48	1.98 0.32	1.44 0.46
1200-Foot	0.73 1.00	0.83 1.33	1.13 0.60	1.02 0.52	1.10 0.66	1.57 0.54	0.95 0.93
Average	1.26 0.66	1.22 0.75	1.55 0.34	1.29 0.42	1.59 0.42	1.77 0.27	

* Top number is normalized strength, S_F/S_L; lower number is normalized residual pore pressure, u_r/u_{ps}

Pore Water Expansion Disturbance

As discussed previously, water expands by about 1.5 percent for a 10,000-foot change in water depth. Since most of the seafloor has a depth less than 20,000 feet, this analysis will consider what happens to a sample whose pore water expands by three percent during retrieval.

Almost all soils have a tendency to expand upon the release of in-situ stress, and it is this tendency to expand that creates residual negative pore pressures. If soil has free access to water, the soil actually does expand. The expansion of pore water is almost exactly analogous to exposing a sample to free water. The only difference is that when a sample is exposed to water, the water must flow into the sample, and there is a time lag. With pore water expansion, the response is immediate.

The influence of pore water expansion may then be evaluated using experience gained through standard consolidation testing. In a consolidation test, samples are first loaded to a particular stress level. The stresses are then reduced incrementally, and the expansion of the sample is measured. The expansibility of the sample is expressed in terms of the swell index, defined as the change in void ratio resulting from a log cycle decrease in vertical stress. Unpublished NCEL data derived from a variety of shallow and deep sea soils indicate that the swell index is usually equal to about 0.1, with very little variation.

Considering the water expansion problem, if the soil void ratio in-situ were 2.0 (a typical value), a 3 percent change would cause the void ratio to be 2.06 after retrieval, a net change of 0.06. With a swell index of 0.1, this expansion is the equivalent of a 0.6 log cycle reduction in vertical effective stress or about 75 percent. The cause-effect relationship is reversible; if a change in stress can cause a change in void ratio, then a change in void ratio will cause a corresponding change in the locked-in effective stresses, as expressed by the residual negative pore pressure. It may be concluded, therefore, that sampling and retrieving a soil under the conditions that have been assumed leads to a reduction in residual pore pressure of 75 percent by virtue of the water expansion.

It is felt that the disturbance effects (reductions in residual negative pore pressure and strength) produced by pore water expansion are very similar to those produced by the particle reorientations caused by mechanical disturbance at constant water content. Thus, residual negative pore pressure changes produced by pore water expansion would be treated in essentially the same way as those produced by mechanical disturbance. From Figure 6, a 75 percent reduction in residual negative pore pressure indicates a strength reduction of about 40 percent for soil at constant void ratio. Other forms of disturbance also occurring during pore water expansion, including a slight increase in void ratio and an elongation of the sample in the core liner, should lead to a somewhat greater amount of strength reduction.

In general, pore water expansion can produce a relatively large

amount of disturbance. However, if residual pore pressure measurements are made, it is possible to compensate for it by using the framework of this report. Also samples from shallower water or with lower void ratios would be less disturbed.

A few, unique soils may be more troublesome. There are the soils with such rigid interparticle bonding and such inflexible mineral grains that the soil would not expand under free water source conditions as much as the water expands during sample retrieval (very small swell index). The interparticle structure could be destroyed in this case, although a slight amount of water flow out of the sample is equally plausible. The extent of disturbance under these conditions could only be determined through an experimental study involving in-situ and laboratory shear testing. These problem soils should be rare, because an unusually low swell index is required. Also, soils with rigid grains and cemented interparticle bonds usually have relatively high permeabilities, making the possibility of water flow more probable.

Gas Expansion Disturbance

Gas-expansion-induced disturbance was not investigated directly with the Santa Barbara Channel samples since none of these contained significant amounts of dissolved gas. However, the author, as a participant in Leg 19 of the Deep Sea Drilling Project, observed several Bering Sea and North Pacific Ocean cores which had obviously undergone significant disturbance by this mechanism. Gas bubbles were visible, and several of the cores were protruding from their barrels. Severe distortion of engineering properties was apparent. On one highly gaseous core from a sediment depth of 2,175 feet, the vane shear strength was 0.13 psi. Using a conservative estimate of the rate of strength increase with depth, the in-situ strength must have been at least 60 psi, or a ratio of in-situ to measured strength of at least 460. It would be impossible to develop curves such as Figure 5 to compensate for such extreme disturbance. Therefore, it is concluded that laboratory testing of samples disturbed by severe gas expansion is meaningless. Either in-situ testing or retention of seafloor pressures during sampling and testing is required.

It may in some cases be difficult to recognize samples that contain moderate amounts of gas. One indicator is a low degree of saturation. Another, discovered during the Deep Sea Drilling Project testing, is a large reduction in the ability of gaseous sediment to conduct sound waves.

In samples with a moderate gas content the residual negative pore pressure may be moderately high since only discrete portions of the interparticle fabric are disturbed. Therefore, in order to make a complete estimate of the extent of disturbance in samples, it is recommended that the extent of gas disturbance be determined by measuring the degree of saturation or acoustic transmissivity.

SUMMARY

1. The critical sample disturbance mechanisms were determined, and an experimental test program was developed to investigate the importance of several of the mechanisms. As a result of this program, a general framework for analyzing the extent of disturbance in seafloor soil samples was developed. This framework is based on the work of Ladd and Lambe (1963) and is summarized by the curve in Figure 5. This curve is a plot of the ratio of field to laboratory vane strength versus the ratio of laboratory residual pore water pressure to a reference residual pore pressure. By measuring the laboratory vane strength and pore water pressure and estimating the reference pore pressure, it is possible to obtain a good estimate of the in-situ shear strength. The reference pore pressure may be estimated from Equation 1 if the parameter K_o is known. This parameter may be obtained from Figure 4 and an estimate of the overconsolidation ratio. This estimate may often be made intuitively, although usually a consolidation test is required.

The remaining items related to the influence of the specific disturbance mechanisms.

2. Mechanical disturbance. Sampling and handling cause changes in engineering properties. Two samplers investigated (NCEL fixed-piston and Lehigh gravity) recovered high quality samples of moderately plastic soils (plasticity index greater than 20 percent) and more disturbed samples of less plastic soils. A standard handling procedure, involving storage under refrigeration and 100 percent humidity and testing soon after sampling, appeared to yield a minimum amount of disturbance. Samples vibrated at high and low frequency were more disturbed (additional 25 percent strength reduction), but the disturbance can be compensated for by using the residual pore pressure framework of Figure 5.

3. Porewater expansion was investigated analytically. It was determined that strength reductions on the order of 40 percent might occur when sampling soils from the deeper portions of the oceans. However, the extent of this disturbance is compensatible using the residual pore pressure framework. A few problem soils which have rigid interparticle bonding require additional investigation.

4. Significant gas expansion was determined to cause an intolerable amount of disturbance that could not be evaluated using residual pore pressures. Based on the experience of the author, however, most seafloor soils do not contain enough gas to cause extreme disturbance.

5. Temperature effects were not investigated directly. However, existing research (Mitchell, 1969) indicates that non-time-dependent properties are not strongly affected if testing is performed at the highest temperature the sample has ever experienced. This procedure was followed in the tests summarized in this report.

6. Organic material decomposition was found to cause significant disturbance. Samples stored without refrigeration for periods of time ranging between one and six months changed color and developed strong odors. The strength reduction was on the order of 25 percent but could be evaluated using the residual pore pressure approach.

7. Water content changes were most significant with cores stored vertically. Well-sealed, horizontally stored cores appeared to maintain their water contents even when stored for as long as one year.

8. Long-term storage did appear to affect the engineering properties (40 percent vane strength reduction), probably as a result of a creep mechanism. The disturbance could be evaluated using residual pore pressures.

9. Core shortening was not investigated in this study. The two corers used were designed to minimize this problem.

CONCLUSIONS

1. The rational design of foundations or anchorage systems for seafloor installations requires a knowledge of the soil engineering properties in-situ. It is possible to calculate the in-situ shear strength of a seafloor soil from the results of laboratory shear strength tests on samples. A significant disturbance corrections is usually required since the two strengths may differ by 50 percent or more. The residual negative pore pressure retained by a sample is a good measure of disturbance.

2. Careful core handling procedures can reduce disturbance and, therefore, increase the credibility of results obtained. However, most poor handling practices can be compensated for approximately. It also appears possible to compensate for unavoidable forms of disturbance such as pore water expansion.

3. Gas expansion appears to be one of the most severe forms of disturbance. It may be impossible to estimate the in-situ shear strength through testing of a sample containing a significant amount of gas.

RECOMMENDATIONS

1. The procedures of this report are recommended for estimating the in-situ shear strength of a cohesive, near-shore seafloor soil. To apply these procedures it is necessary to obtain a bottom core sample, measure its residual negative pore pressure and vane shear strength, and use the curve of Figure 6' to obtain the in-situ strength. The parameter, u_{ps} (reference residual pore pressure), is required in the

use of Figure 6 and may be calculated from Equation 1. A procedure for obtaining the parameters of Equation 1 is provided in this report, although, in some cases, the performance of a consolidation test is required in order to follow the procedure. For most typical, soft seafloor soils, the parameters provided in Table VII for the 1200-foot site may be used directly.

2. These procedures may not be used with samples containing a significant amount of gas. In questionable cases, the extent of gas expansion occurring during sampling should be determined by measuring either the degree of saturation or acoustic transmissivity.

3. The following core handling procedures are recommended:

   a. Cut cores into relatively short (1 to 2-foot) sections shortly after they are taken.

   b. Seal sample sections carefully by tightly taping covers to ends and dipping in a non-brittle, impervious wax (for example, a paraffin-silicon wax mixture).

   c. Place samples under refrigeration at near seafloor temperatures soon after they are taken; preferably on shipboard. Store horizontally.

   d. Prevent vibrations and jolting.

   e. Perform vane shear and residual pore pressure tests promptly, allowing only a short storage period.

   f. Perform short-term tests at the highest temperature to which the samples have ever been subjected.

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REFERENCES

Anderson, D. G. and H. G. Herrmann (1971). "Seafloor Foundations: Analysis of Case Histories," Naval Civil Engineering Laboratory Technical Report R-731, Port Hueneme, CA.

Beard, R. M. (1972). "The Effect of Perfect Sampling on the Strength of a Marine Clayey Silt," Unpublished MS Thesis, University of California, Los Angeles.

Bjerrum, L. and Simons (1960). "Comparison of Shear Strength Characteristics of Normally Consolidated Clays," ASCE Conference on Shear Strength of Cohesive Soil, Boulder Colorado, pp. 711-726.

Brooker, Elmer W. and H. O. Ireland (1965). "Earth Pressures at Rest Related to Stress History," Canadian Geotechnical Journal, Vol. II, No. 1 (Fil).

Casagrande, A. (1936). "The Determination of the Pre-consolidation Load and Its Practical Significane;" Proc. First International Conference on Soil Mechanics and Foundation Engineering (Cambridge, Mass.), p. 60.

Crisp, H. A. (1968). "The Measurement of Pelagic Submarine Soil Strength," Unpublished M. S. Thesis, George Washington University.

Demars, K. R. and R. Taylor (1971). "Naval Seafloor Sampling and In-Place Equipment: A Performance Evaluation," NCEL Technical Report R-730, Port Hueneme, CA.

Gibbs, H. J. and C. T. Coffey (1969). "Application of Pore Pressure Measurements to Shear Strength of Cohesive Soils", U. S. Bureau of Reclamation Report No. EM-761, Denver, Colorado.

Halwachs, J. E. and N. T. Monney (1972). "Analysis of Sediment Shear Strength at Varying Rates of Shear," 18th Annual Meeting of the Institute of Environmental Sciences, New York, NY.

Herrmann, H. G., K. Rocker, and P. Babineau (1972). "LOBSTER and Foundation Monitor System: Devices for Monitoring Long-Term Seafloor Foundation Behavior," NCEL Technical Report R-775, Port Hueneme, CA.

Hvorslev, M. J. (1949). "Subsurface Exploration and Sampling of Soils for Civil Engineering Purposes," Report of Committee on Sampling and Testing, Soil Mechanics and Foundation Division, American Society of Civil Engineers.

Jacobson, B. (1954). "Influence of Sampler Type and Testing Method on Shear Strength of Clay Samples," Royal Swedish Geotechnical Institute Proceedings No. 8.

Kallstenius, T. (1958). "Mechanical Disturbances in Clay Samples Taken with Piston Samplers," Royal Swedish Geotechnical Institute Proceedings No. 16.

Kretschmer, T. R. and H. J. Lee (1970). "Plate Bearing Tests on Seafloor Sediments," NCEL Technical Report R-694, Port Hueneme, CA.

Ladd, C. C. and T. W. Lambe (1963). "The Strength of 'Undisturbed' Clay Determined from Undrained Tests," ASTM Standard Technical Publication No. 361, pp. 342-371.

Lambe, T. W. and R. V. Whitman (1969). Soil Mechanics, John Wiley and Sons, New York, p. 127.

Migliore, H. J. and H. J. Lee (1971). "Seafloor Penetration Tests: Presentation and Analysis of Results," NCEL Technical Note N-1178, Port Hueneme, CA.

Mitchell, J. (1969). "Temperature Effects on the Engineering Properties and Behavior of Soils," Highway Research Board Special Report 103, pp. 9-28.

Monney, N. (1967). "Engineering Aspects of the Ocean Floor," Unpublished PhD Dissertation, University of Washington.

Noorany, I. and H. B. Seed (1965). "In-Situ Strength Characteristics of Soft Clays," American Society of Civil Engineers, Proceedings, Journal of the Soil Mechanics and Foundations Division, Vol. 91, No. SM2, pp. 49-80.

Padilla, J. R. (1971). "Deep Ocean Test-in-Place and Observation System (DOTIPOS) for Naval Seafloor Construction Support," NCEL Technical Report R-752, Port Hueneme, CA.

Richards, A. and H. W. Parker (1967). "Surface Coring for Shear Strength Measurements," in Civil Engineering in the Oceans, ASCE Conference, pp. 445-488.

Singh, A. and J. Mitchell (1968). "General Stress-Strain-Time Function for Soils," ASCE Journal of Soil Mechanics and Foundations Division, Vol. 94, No. SM1, pp. 21-46.

Skempton, A. W. and V. A. Sowa (1963). "The Behavior of Saturated Clays During Sampling and Testing," Geotechnique, Vol. 13, No. 4, pp. 269-290

Taylor, R. and K. Demars (1971). "Naval In-Place Seafloor Soil Test Equipment: A Performance Evaluation," NCEL Technical Note N-1135, Port Hueneme, CA.

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13. ABSTRACT

The major obstacle to rational design of seafloor foundations and anchors has been a lack of good quality information on the bottom sediment engineering properties. Considerable engineering property data have been obtained through laboratory testing of core samples, but most of these data are of questionable validity because of the sample disturbance factor. To improve the usability and credibility of laboratory test data, an experimental investigation was undertaken to determine the extent of disturbance involved in seafloor soil sampling and handling. In-situ tests were performed and related to comparable laboratory tests. The soils tested were from the Santa Barbara Channel with a terrigenous (land-derived) origin. A technique based on earlier work was developed for predicting in-situ shear strength on the basis of laboratory test results. Various disturbance mechanisms including sampling, vibration, long-term nonrefrigerated storage, and water and air expansion were investigated and analyzed quantitatively. Strength reductions varying between 15 and 50 percent were observed to result from these disturbances. The in-situ strength prediction procedure appears to be capable of compensating for all forms of disturbance except for those developing as a result of gas expansion.

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